The Urban Heat Island, Photochemical Smog, and Chicago: Local Features of the Problem and Solution

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EXECUTIVE SUMMARY

High rates of urbanization have resulted in drastic demographic, economic, land use, and climate changes. The growth and expansion of cities entails the construction of new roads, buildings, and other human made structures to accommodate the growing population, and in turn, the destruction of the natural ground cover and landscape. As a result, urban microclimates, referred to as urban heat islands, with elevated air temperatures of 2-8°F, increased energy demands, and elevated pollution concentrations are created.

It has been proposed that as a result of a decrease in temperature, the modification of an urban surface to include more vegetative cover and lighter, lower albedo surfaces would also reduce ozone exceedances, energy consumption, and detrimental environmental and human health effects associated with high levels of ozone. Chicago is among the cities classified as a severe ozone nonattainment area, and is the focus of this study. The purpose of this investigation is to characterize the ozone and temperature relationship in the Chicago area, review strategies that diminish ambient urban temperatures, with particular attention to comparing the total costs associated with asphalt and concrete pavement design, and present the results of an urban fabric analysis for Chicago that reveals areas and land uses where cooling strategies may have the greatest impact.

The Chicago area ozone and temperature relationship was found to have a rather weak correlation, which suggests that there are other factors present that dictate the quality of Chicago's air. In fact, our analysis, in conjunction with studies conducted by the Ozone Transport Assessment Group (OTAG), established that Chicago's ozone problem is strongly correlated with local and regional wind patterns and atmospheric transport. There is, however, a clear temperature threshold. Over a five year period for 13 monitoring stations, ninety percent of the ozone exceedances in the metropolitan area occurred at temperatures above 80°F and the likelihood of smog events increases at extreme temperatures over 95°F.

The temperature profile of Chicago showed that the actual heat island in the Chicago area consistently appears in the western suburbs (specifically over Lisle), not in the Downtown area. An examination of the ozone data for the Chicago area, specifically Cook County, revealed that the majority of the noncompliance days are not located in Downtown Chicago. Instead, they appear to center around the northern suburbs.

When the heat island and ozone levels in various locations of Chicago are compared, it is observed that the areas having a greater frequency of ozone noncompliance do not correspond to the heat island and these areas are located in a region with few known emissions sources. The result of this comparison supports the hypothesis that atmospheric and surface transport mechanisms greatly influence the ozone distribution in the Chicago area. In addition, this observation indicates that the occurrence of elevated ozone concentrations is a regional issue, although it can be assumed that that a portion of the ozone originates from within the domain as a result of the reactions of O_3 precursors.

Urbanization of the natural landscape through the replacement of vegetation with roads, bridges, houses, and commercial buildings has dramatically altered the temperature profile of cities. While many of the factors that influence the formation of urban heat islands, including climate, topography, and weather patterns, cannot be changed or altered, there are efficient and cost-effective ways of mitigating heat islands exist. Two heat island factors attributable to human activities can be readily controlled: the amount of vegetation and the color of surfaces.(3) Increasing vegetative cover through strategic landscaping around buildings and throughout cities

can absorb solar radiation, provide shade, and control wind flow benefits. Changing dark colored surfaces to light colored ones would more effectively reflect, rather than absorb, solar energy and emit stored heat energy at a higher rate, thus reducing the cooling energy loads and ground level air temperatures influenced by these surfaces.

While little resistance is typically encountered in devising programs to increase tree plantings and vegetative cover, greater obstacles are met with efforts to change construction and paving practices. This report has focused on evaluating the impacts and costs associated with asphalt verses concrete pavement.

Traditionally in life cycle cost analysis, an emphasis has been placed on the respective costs of different pavement alternative throughout their lifetimes. As a result, when concrete and asphalt systems are compared, the asphalt pavement alternative is usually selected because a concrete system is more expensive to construct and maintain.(35) Life cycle assessment, using environmental value engineering, employs a systems approach methodology to more accurately compare the input requirements and related environmental impacts of pavement alternatives.(42) As a result, when concrete and asphalt highway pavement systems are compared using this revised life cycle analysis approach, concrete proves to be superior. In fact, it has been shown that based on a normalized unit of comparison, overall concrete is approximately 47.6% more efficient than asphalt.

Land use and surface cover are elements of the urban fabric that are commonly altered during the development of metropolitan areas. Because these elements, which include vegetation, building roofs, and pavements, act as the active thermal interfaces between the atmosphere and land surfaces, their composition and structure within the urban canopy layer largely determines the thermal behavior of different areas within a city. Thus, the alteration of these surfaces results in the creation of numerous urban microclimates; the combined result of which is referred to as the heat island effect.(52)

In order to accurately analyze the effect of surface cover modifications, attain pertinent results, and eventually simulate realistic estimates of temperature and ozone reductions resulting from these modifications, the current urban fabric of the Chicago must be quantified as it relates to land use.

Based on our urban fabric analysis it was found that the residential vegetative cover is relatively high, above 45%, over all the different density areas within the city of Chicago. Thus, it is also concluded that Chicago is already doing a relatively good job in the residential areas with respect to maintaining a high vegetative cover to paved surface ratio, of approximately 2.2-4.2. In contrast, the commercial and industrial areas in the Chicago area have the least proportion of vegetative cover, about 10-16%.

The analysis of roofed surface cover revealed that this proportion is dependent upon the building density within a particular land use category. Thus, it was observed that recreational and far suburban residential areas contain the least portion of roofed surfaces, less than 13%, for they have the lowest building density associated with them. In addition, when light/white roofs were separated out, it was revealed that lighter roofing materials are already in wide use in Chicago with the greatest percentage of light/white roofs was found in commercial areas, 66-90%. This point illustrates the feasibility of employing light roofing materials, in the construction and resurfacing of building roofs, as a heat island mitigation strategy in the Chicago area. Specifically, an emphasis should be placed on the suburbs where a high degree of development is occurring.

The paved surface cover was found to be the greatest in the transportation, commercial, and industrial areas, where its proportion is above 50%. In addition, the vegetative cover to paved surface ratio in these three areas is small, about 0.2-0.5. As a result, an emphasis should be placed upon developing and implementing mitigation strategies within the transportation, commercial, and industrial areas of Chicago. These mitigation strategies should include a focus on greater use of concrete over asphalt, and in general, should encourage the use of higher albedo paving materials the suburban areas that almost exclusively use asphalt for pavement. However, a change to the utilization of concrete over asphalt will require urban and suburban planners to compare costs over longer design lives and consider all the environmental costs associated with a material's use, neither of which is currently done. The life cycle analysis reviewed herein presents one methodology for making such a comparison.

The use of cooling strategies, such as increased vegetation and use of high albedo surfaces, if applied to the metropolitan Chicago area may be expected to produce a decrease in temperature, similar to that predicted for the LA Basin. However, most ozone noncompliance days are not solely the result of temperature effects and the majority occurs at temperatures above 85°F. Therefore, a 4°F decrease in temperature, as observed for surface modification simulations within the LA Basin (3,4), would probably have a similar, small effect by promoting a 10-12% reduction in the overall number of ozone noncompliance days in the Chicago area. Based upon observed data, a 10-12% reduction in the total number of ozone noncompliance days would translate into only approximately 0.6 days per year. Therefore, it is important to consider and examine more fully the other benefits, in addition to lower ozone levels, that are promoted by cooling strategies. These additional benefits include reduced energy demands, increased health protection, and increased comfort.

1. INTRODUCTION

1.1 PROBLEM STATEMENT

The purpose of this project is to identify the effect that surface modifications have on the urban heat island phenomenon and related ozone problem in the metropolitan area of Chicago, IL. The basic hypothesis is that urban, summertime temperatures can be significantly lowered by increasing the vegetative landscape cover and enhancing the solar reflectivity of paved and roofed surfaces within an urban area. It is proposed that in addition to a decrease in temperature, the modification of an urban surface to include more vegetative cover and lighter, lower albedo surfaces will also reduce energy consumption, ozone exceedances, and detrimental environmental and human health effects associated with high levels of ozone.

The analysis is divided into three main parts. The first section of this report introduces the causes of ground level ozone and its effects in urban areas. It explains both the chemistry and transport associated with ozone exceedances. The second section is a compilation of the most viable mitigation strategies of urban heat islands: increasing vegetative cover and increasing proportions of light to dark surfaces. The effects, implementation strategies, and specific strengths and weaknesses associated with each approach are described, including a comparison of asphalt and concrete pavements systems using a life cycle analysis approach. The final section provides a case study of the Chicago area. This study entailed an examination of the land use, development of an urban fabric analysis in which total vegetative, paved, and roofed surfaces are investigated and quantified, and discussion on the effectiveness of possible mitigation strategies in the Chicago area. In general, the associated findings of my research are located within this final section.

1.2 OBJECTIVES

The overall goal of this project is to investigate the relationship between the urban heat island phenomenon, the ozone problem, and the effect of urban surface cover and color modifications in the metropolitan area of Chicago, IL.

The specific objectives of this work are to:

- Review the detrimental effects of the urban heat island phenomenon, particularly as a causative factor in promoting exceedances of air quality ozone standards, and identify mitigation alternatives that may reduce the effects of the urban heat island.
- Illustrate the differences in temperature between the urbanized center of Chicago and the surrounding areas in order to identify the heat island in the Chicago region.
- Examine the spatial distribution of ozone levels in the Chicago area and consider probable sources.
- Evaluate of the relationship between temperature and ozone.
- Develop a method to analyze the urban fabric of the Chicago area from aerial photographs, thus allowing the determination of the proportion of vegetative, roofed, and paved surfaces as a function of land use.
- Evaluate of the effectiveness of possible mitigation strategies as applied to the Chicago area, with special focus on vegetation and paving materials.